T2 Working Group Summary
August 12, 2001

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Introduction

The T2 Working Group has reviewed and discussed the issues and challenges of a wide range of magnet technologies; superconducting magnets using NbTi, Nb_3Sn and HTS conductor with fields ranging from 2 to 15 Tesla and permanent magnets up to 4 Tesla. The development time of the various technology options varies significantly, but all are considered viable, providing an unprecedented variety of choice that can be determined by a balance of cost and application requirements.

One of the most significant advances since Snowmass '96, is the increased development and utilization of Nb_3Sn. All of the current US magnet programs, BNL, FNAL, LBNL and Texas A&M have programs using Nb_3Sn. There are also active programs in HTS development at BNL and LBNL. A DOE/HEP sponsored program to increase the performance and reduce the cost of Nb_3Sn is in the second year. The program has already made significant improvements. The current funding for this program is $500k/year and an increase to $2M has been proposed for FY02.

US Magnet Programs

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The primary goal of the magnet R&D program at BNL is to develop magnet designs and technology where high temperature superconductors (HTS) play a major role. The performance and availability of high temperature superconductors have reached levels that allow serious magnet R&D to be started. HTS has many potential advantages, including operation at elevated temperature in an environment where a large amount of energy is deposited by decay particles. This makes HTS particularly attractive for interaction region magnets of various colliders and for storage ring magnets of a muon collider. The other major advantage is that, unlike low temperature superconductors (LTS), HTS retains most of its current-carrying capacity at high fields.

Despite the above-mentioned advantages, HTS is a difficult material to work with, as it is brittle in nature and requires a well-controlled reaction environment. It will require long term R&D (several years) before a magnet based on HTS can be used in particle accelerators. The magnet designs must be "conductor friendly". BNL is developing several such designs (including the common coil design concept for VLHC) that are based on racetrack coils with large bend radii, suitable for "React & Wind" technology. BNL is also building racetrack coil magnets with open midplane gaps for a neutrino factory storage ring. A new design, where ends provide skew quadrupole focusing, eliminates space wasted in the ends. In addition, the quadrupole magnets for VLHC interaction regions and an LHC interaction region upgrade are also being developed using the same general technology.

In addition to developing several new magnet designs, BNL has developed a magnet R&D program with rapid turn around. It has made and tested many short HTS and Nb_3Sn coils based on cables and tapes. The performance of these HTS coils has been very encouraging so far. The next phase of the BNL program will be to make field quality measurements in magnets built with HTS coils and to test the HTS coils in a 12 T background field generated by Nb_3Sn superconductor.

HTS material development is being carried out in industry with significant funding from places other than High Energy Physics (HEP). The industry has made major advances in terms of producing longer length wires/tapes, large-scale production, and improvements in material properties.

Fermi National Accelerator Laboratory

The Stage-2 magnet system configuration with the vertical bore arrangement adopted in this study dictated the configuration of the superconducting magnets described in the *VLHC Design Study Report*. Arc dipole magnets are based on the common coil design and react-and-wind fabrication technique. This is regarded at this time as the most innovative and cost effective approach, although it requires significant efforts to prove it experimentally. Extensive R&D efforts in this direction are in progress at Fermilab, LBNL and BNL. Single-layer common coils with 25 kA and 90 kA nominal current were developed at Fermilab. There are also other magnet design approaches based on the traditional cos-theta (shell-type) coil geometry that allows both horizontal and vertical bore arrangements. These magnets based on two-layer and single-layer coils are being developed at Fermilab for the VLHC and meet the Stage-2 VLHC requirements; including operating field range, field quality, critical current and critical temperature margin, quench protection, etc. [i]. The designs and parameters of arc quadrupole magnets that match these dipole magnets are described in [ii, iii].

Due to the small bending radii in the cos-theta type coils, we are forced to use the wind-and-react technique in order to avoid a large degradation of the cable critical current during coil winding. These coils can be placed much closer to each other, especially in the horizontal bore arrangement, reducing the iron yoke size and the total magnet size, weight and cost.

Lawrence Berkeley National Laboratory

The LBNL superconducting magnet program is primarily directed towards development of high field magnets for future accelerators. At present, accelerator magnet technology is dominated by the use of NbTi superconductor. To achieve fields above 10 Tesla requires the use of A15 compounds, the most practical and available of which is Nb_3Sn. In a practical geometry, magnets based on Nb_3Sn technology should be able to exceed fields of 14 -15 Tesla at 4.2 K. The challenge lies in incorporating the intrinsically brittle, strain sensitive material, into a realistic magnet where it is subjected to stresses that could exceed 150 MPa. Advances in fabrication techniques and materials have allowed us to reinvestigate simple racetrack coil geometries that have advantages in support structure design and fabrication.

In FY 98, the emphasis of our high-field magnet work shifted from "proof of principle" to a broad-based search for a cost-effective magnet solution for the next generation collider beyond the LHC. This shift is consistent with the recommendations of the High-Energy Physics Advisory Panel (HEPAP) subpanel on Planning for the Future of U.S. High Energy Physics, sometimes known as the "Gilman Panel." These recommendations include a statement that "an expanded program of R&D on cost reduction strategies, enabling technologies, and accelerator physics issues for a VLHC" is desirable. This slightly more focused approach fits within the overall goal of the program to "write the book on magnets".

In particular, we are concentrating on the common coil configuration for its potential simplicity of construction and consequent cost effectiveness. The design concept consists of a pair of racetrack coils shared between two apertures, producing fields in opposite directions. This geometry is intrinsically suited for a collider, but modifications of this design can be used for single-aperture applications as well.

Texas A&M University

The accelerator physics group's magnet program is based on interdependent avenues of approach to a future machine magnet ring based on high field, high current density, wind and react, and *internally stress managed* windings. The first avenue of approach is that of extensive design studies, which are concentrating at the present time on several tasks, one of which is a "common coil" variation in the 14 – 16T range with bore size range in the 30 to 40mm diameter. These designs are based on race track coils which contain internal high strength (Inconel 708, and Titanium) support structures to limit stress integration and intercept it across the winding packages. There is another design study driven by the concept of a "Tevatron Tripler" which is centered around block coil designs with a single aperture which result in dipole fields of 12 – 13T, and quadrupole gradients of 425T/m. Another design study being pursued is driven by the "Muon Collider" ring concept and it's associated large heat load around the ring at and near the mid-plane. There is also a sectored cyclotron winding concept study underway for a non-HEP application. The latest VLHC design direction for a future machine being computed is that of a small aspect aperture block magnet with a 20mm high and 30mm wide bore.

Concurrently, preceeding on the second avenue of approach during the 1999 to 2000 year period, the group constructed one coil set of a common coil, which was subsequently tested at the end of 2000. The windings utilized NbTi conductor, but included all the material except the A15 superconductor and most of the techniques necessary to produce an A15 conductor winding (i.e. Nb_3Sn..) with a "wind & react" procedure (i.e. "S" glass insulation, fully impregnated block coils, e.t.c…) as well as the stress management internal structure. This prototype performed very satisfactory achieving "short sample" 6.7T, 4.3K in six spontaneous quenches. The present prototype design under construction is a 12 – 13T "Tevatron Tripler" type Nb_3Sn winding with a single aperture. The first phase is utilizing "ITER" project surplus conductor in order to benchmark and trouble shoot the various processing lines and fixtures developed as well as the presently foreseen winding procedures. It is an open question at this point as to whether this coil will be tested in a magnetic mirror configuration or not. The next set of coils will be a complete set of both inner and outer windings using high performance Nb_3Sn/Cu conductor in a mixed strand cable conductor (a cost reduction configuration). This set of coils are the same as presented in the design paper at ASC 2000 in Virginia Beach with the main differences in the structural material of choice for better thermal co-efficient characteristics compatibility, and an additional inter layer ferric plate for low field harmonic correction. The outer support structure is still an aluminum outer shrink ring tube over the vertically split iron return yokes loaded against the winding package with metal filled pressurized stainless steel blatters transmitting the “Lorentz Loads” to the outer structure.

Collider Magnets – *A. Zlobin*

At the present time four superconducting accelerators, the Tevatron (FNAL), HERA (DESY), Nuklotron (JINR) and RHIC (BNL) are in operation, and LHC (CERN) is under construction. All these machines utilize different SC magnets based on the NbTi superconductor and cooled by LHe at a temperature of 1.9 (LHC) or 4.5 K (all the rest).

Recently performed design study for VLHC based on two stage scenario in the 233 km tunnel demonstrated a feasibility of pp collider with c.m. energy of 40 TeV in the first stage with 2 T SC magnets and 175-200 TeV c.m. energy in the second stage with 10 T magnets. The designs of arc dipoles, quadrupoles and correctors that meet the VLHC requirements have been developed.

The 10 T arc dipoles use a design based on the common coil approach and cold iron yoke. This common coil dipole design is a simple single-layer coil divided into three blocks by wide spacers. It simplifies the design and fabrication technology, and allows the possibility of using reacted brittle Nb_3Sn cable, solving mechanical problems, and at the same time achieving excellent field quality. The coils are made of rectangular Rutherford-type cable with 60 Nb_3Sn strands, each 0.7 mm in diameter.

The 400 T/m arc quadrupole magnet with vertical bore arrangement and FF or DD functions matches the arc dipole magnet. The magnet design is based on a two-layer shell-type coil and cold iron yoke. The coil utilizes a keystone Rutherford-type cable made of 28 Nb_3Sn strands, each 1 mm in diameter.

The arc correction system includes dipole, quadrupole and sextupole correctors combined in two packages: a) 2.3 T*m dipole and 0.74 T*m/cm^2 sextupole package for the arc cells and b) 2.3 T*m dipole and 0.95 T*m/cm skew-quadrupole package for DS cells. Taking into account the availability of well-developed technologies for NbTi correctors, they were chosen as a baseline approach. The VLHC-2 IR magnets are discussed elsewhere (see WG T1 report).

Quench heaters installed in the dipole and quadrupole magnets distribute the stored energy deposition throughout the coil, protecting it from overheating and preventing insulation damage from the high voltage and thermo-mechanical stress.

With a proton energy of 87.5 TeV per beam and a bending radius of 29.9 km, the synchrotron radiation power emitted by the two beams is 9.4 W/m. A beam-screen is inserted inside the magnet cold bore to intercept this power. The beam-screen is perforated over its surface, to allow cryopumping to the 5 K cold bore surface.

The dipole and quadrupole cryostats are 958 mm wide and 1012 mm high. Their lengths are approximately 17 m and 9 m and total estimated weights are 42 tons and 22 tons respectively. The spool nominal length is 2.5-3 m. Spools exist in several varieties, e.g. with and without vacuum breaks, with and without high-current dipole and quadrupole leads, etc. All the large cold pipes and most of the electrical bus are placed in a separate transfer line to simplify magnet interconnects.

Magnets are cooled by a flow of supercritical, 4.5 K helium. Allowing a 1 K rise in the helium flow through the magnet string avoid the use of recoolers or two-phase helium. An 80-110 K helium stream cools the thermal shields and beam screens.

Examine in detail the most important and challenging aspects of these technologies, both from the point of view of performance and cost-effectiveness. These aspects should include the development and use of SC materials (including HTS), magnet design for high field quality, magnet fabrication, cryogenic systems and their integration with the magnets, and cold beam vacuum issues.

The NbTi dipole magnets can provide up to 7 T nominal operating field at 4.5 K and up to 9 T operating field at 1.9 K. These values are determined by the NbTi critical parameters such as $B_{c2}(0K)$~14 T and $T_c(0T)$~9.5 K. Thanks to the excellent mechanical properties of NbTi, traditional electromagnet technologies were used in the construction of these magnets. The NbTi accelerator magnets have been mass-produced in Laboratories (Tevatron, Nuklotron) and in industry (HERA, RHIC) at affordable costs.
In order to reach nominal fields above 9-10 T required for the current VLHC-2 and other VLHC scenarios (see report WG M4) alternative superconductors such as A15 materials (Nb_3Sn or Nb3Al), and HTS (BSCCO) as well as different design and technological approaches were considered.

Nb_3Sn has $B_{c2}(4.2K)$=23-24 T and $T_c(0T)$=18 K. Formation of the Nb_3Sn phase and its brittleness determine two possible fabrication techniques: wind-and-react or react-and-wind. In the past 5 years, a feasibility of fields above 10 T at 4.3 K in Nb_3Sn accelerator magnets made using wind-and-react technique has been demonstrated experimentally. The Twente University group (Netherlands) achieved 11 T at 4.3 K with a two-layer cos-theta dipole model. The LBNL group built a four-layer cos-theta dipole model that reached fields above 12.4 T at 4.3 K and above 13 T at 1.9 K. A common coil Nb_3Sn racetrack structure at LBNL recently reached 14.5 T field at 4.3 K.

Available HTS materials include BSCCO-2212, with $T_c(0T)$~85 K, and BSCCO-2223, having $T_c(0T)$~110 K. Kilometer-length quantities of these materials have been made in the form of multifilamentary tapes or round strands, suitable for a magnet using the flat racetrack coil design. Very high critical current densities have been achieved at high fields in YBCO short samples. However, commercial production of this material lags well behind BSCCO. Cost of all HTS materials is very high and their production rate is too low at the present time.

Progress in raising the critical current of Nb_3Sn strands and in developing magnet technologies for brittle superconductors make it possible to design *cost-effective* Nb_3Sn accelerator magnets with a nominal field above 10 T, sufficient operating margins, accelerator field quality and reliable quench protection. Nb_3Sn accelerator magnets employing different coil (cos-theta and block) and iron yoke (warm, cold) designs and utilizing both wind-and-react and react-and-wind fabrication techniques are being investigated in U.S., Europe and Japan. The development and experimental studies of Nb_3Sn strands, cables, and magnets and technologies in U.S. are carried out at BNL, LBNL, TAMU and Fermilab. The works with HTS materials and their applications in accelerator magnet designs are performed at BNL and LBNL.

The cost and performance of RHIC medium-field arc dipoles have often been used as benchmarks in discussions of future accelerators [1]. The cost was scaled to the 30 mm aperture now proposed for VLHC magnets. The result is $1263 per Tesla meter for 18 m long magnets, compared to a cost of $1436 per Tesla meter for the 40 mm RHIC aperture.

[1] E. Willen, “Superconducting Magnets,” INFN Eloisatron Project 34th Workshop, “Hadron Collider at the Highest Energy and Luminosity,” Erice, Sicily, November 4-13, 1996.

Synchrotron Radiation – *P. Bauer*

Introduction

Ever since a post LHC hadron collider is being discussed, synchrotron radiation was identified as one of the major technological challenges. The synchrotron radiation (SR) power emitted by the protons per unit length, scales with the fourth power of particle energy (γ^4), the beam current and ρ^{-2}, where ρ is the arc-bending radius of the machine. Therefore, any energy frontier hadron collider of the future, using high field magnets, is likely to produce several W/m/beam of SR power. The currently proposed VLHC in its second stage, for example, would produce 5 W/m/beam of SR power [1]. This level of radiation power is still far below the level of SR in what is believed to be the last circular electron machine, Cern’s LEP, which generates ~400 W/m/beam. It is possible to imagine hadron collider scenarios, using very high field magnets and accelerating hadrons to extreme energies, such that similar levels of radiation power arise. However, given the technical limitations in magnet technology, limitations related to the cost of the machine and other limitations (such as beam-energy and IR debris power), a more realistic range of radiation powers of 1-30 W/m/beam is most likely to occur in the next generation hadron collider. The following discusses the implications of synchrotron radiation and the possible solutions to the problem of extracting the radiation power (most likely from a cryogenic environment) in this range of radiation powers.

Synchrotron Radiation Power

Error! Reference source not found. shows the calculated SR power level versus machine size (or more precisely the particle trajectory bend radius in the guide field) for various particle energies that are possible in a future VLHC (assuming an average beam-current I_b=100 mA).

The presently known solutions to the problem of extracting the SR related heat load from a cryogenic environment, e.g. with a cooled beam-screen or a photon-stop, have their limitations. The following attempts to explore these solutions in the full range of SR heat loads indicated in the introduction. Schematics of the solutions are shown in Figure 1.

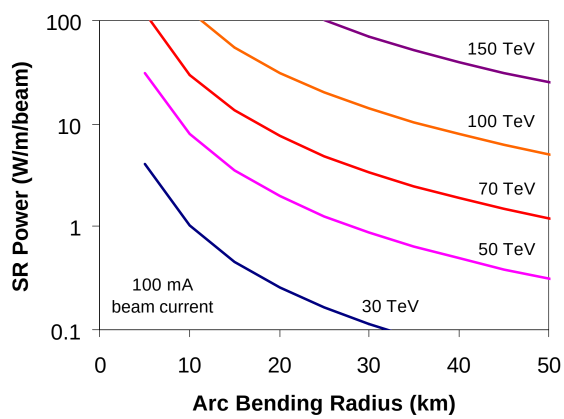


Figure 1: Synchrotron radiation power as a function of arc bending radius for different particle energies (100 mA beam).

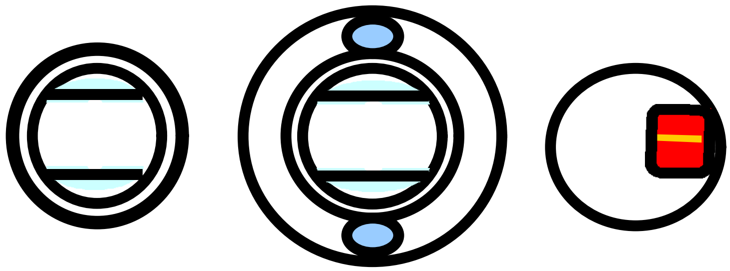


Figure 1: Schematics of different solutions to the SR problem in cryogenic colliders: cooled beam-screen, room temperature beam-screen with internal shield and photon-stop.

Two possible beam-screen configurations are shown: A cooled beam-screen, much like the LHC beam-screen and a room temperature beam-screen with an additional screen.

Beam Screens

The beam-screen solution will look different according to the SR heat load. For a heat load < 10 W/m/beam, a cooled beam-screen - similar to the LHC BS - is a possible solution. To minimize the cryo-power requirements the beam-screen operational temperature has to be raised with increased SR heat load, together with the required He mass flow rate and thus the cooling channel size. Another possible beam-screen solution consists of a room temperature, water-cooled beam-screen surrounded by an 80 K (helium-cooled) shield. The room temperature beam-screen is not attractive at a SR heat load <5 W/m/beam, because it produces a residual heat load of 3.7 W/m/beam (extracted by the "internal" shield placed between the screen and the cold bore), independently of the SR load. In terms of power cost the room temperature beam-screen is the better solution above a SR heat load of 5 W/m/beam. Figure 2 shows the power-cost at the plug per meter per beam for both solutions. The formulas (2), used in these calculations are 2nd order polynomial fits to numerical calculations presented in detail in [2], [3]. The calculations on which **Figure 2** is based, assume 20 bar gaseous helium as the cooling gas, a 135 m length for the cooling loop, a 20 K / 1 bar temperature / pressure drop along the cooling loop, coefficients of conductive and radiative heat transfer between the screen and the cold mass measured at Cern in the frame of the LHC beam-screen development, and operation at the thermodynamically optimal temperature. The optimal temperature rises quickly with increased SR load and reaches ~100 K at ~5 W/m before, saturating at ~120 K at ~20 W/m. Above that load an increase of beam-screen temperature is not favored, because the heat transfer from the screen to the 5 K cold mass becomes prohibitively large. The saturation of the optimal temperature is an indication that an additional shield is required, such as in the case of the room temperature beam-screen.

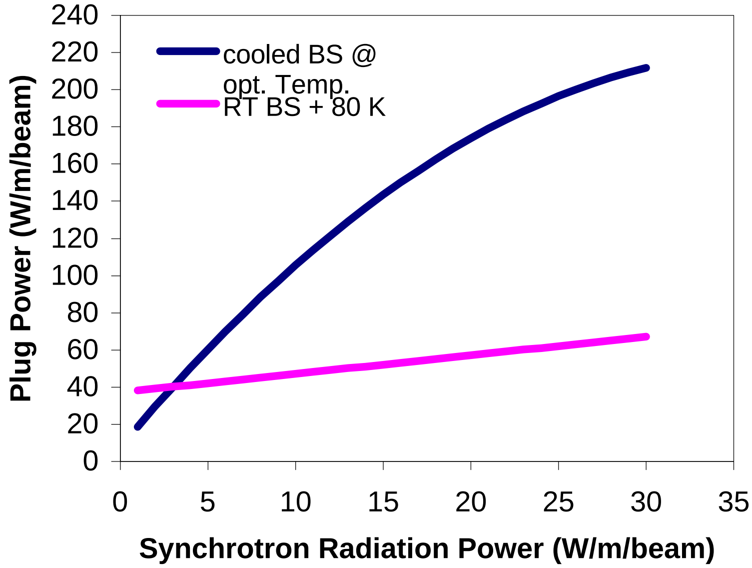


Figure 2: Plug Power for cooled and room temperature beam-screen, per m of machine, per beam.

Although the room-temperature beam-screen solution may appear more attractive at a SR load exceeding 5 W/m, it is not. The room-temperature beam-screen solution requires a larger magnet aperture because of the internal 80 K shield, which makes it un-attractive compared to the more compact cooled beam screen solution. On the other hand, as mentioned above, the cooling channel size requirement in the case of the cooled beam-screen increases with increasing heat load. Therefore, the room temperature beam-screen solution becomes interesting at a SR power load at which the cooled beam-screen becomes larger than the room temperature beam-screen (whose size is in first approximation SR load independent). Figure 3 shows the result of a calculation of the required aperture for the beam-screen solutions as a function of SR heat load. As can be seen in this plot the crossing occurs at ~20 W/m/beam. The calculations on which Figure 3 is based are described in the following. The aperture requirement is estimated from the sum of the equivalent diameters of the various components. First, the minimum beam area assumed in these calculations is a circle with Ø 20 mm. Then, the equivalent diameters of the cold-bore wall (2·1.5 mm), the insertion gap and support rings (2·1 mm) and the cooling tube wall (2·1.5 mm) are calculated from their respective thickness (multiplying the thickness by 2). The equivalent diameter of the required coolant flux as a function of SR power is calculated with a fit to numerical data presented in [2]. In the case of the RT beam-screen the size of the screen cooling channels (5.3 mm) and the 80 K shield (13 mm) are assumed to be constant. The additional internal shield in this case requires a second set of gaps and supports.

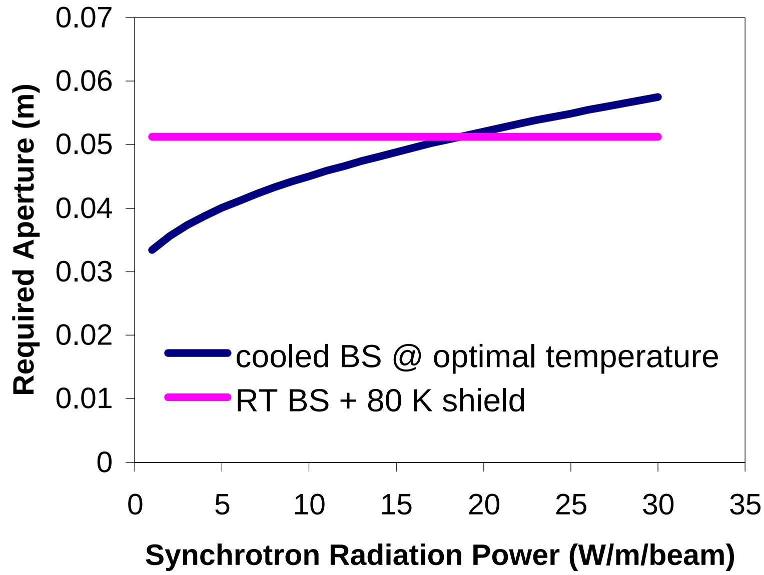


Figure 3: Aperture requirements for the cooled BS and RT-BS as a function of SR heat load.

All beam-screen solutions, especially in a large ring, entail large cryo-power requirements and cost. The SR power load in these plots was therefore restricted to ~30 W/m/beam. The cryo-power cost and especially the cost of the enlarged magnet aperture are considerable. The enlarged aperture can be avoided in magnet designs, which have larger vertical apertures (e.g. block-type coils), where large cooling capillaries can be accommodated without increasing the horizontal aperture.

Photon-Stops

The photon-stop will always be the preferred solution (compared to a beam-screen), because it extracts the SR heat load at room temperature and thus at optimal Carnot efficiency. Unfortunately it remains to be proven that it works. Critical issues of the photon-stop design are primarily related to the surface power-density and secondarily to its impedance. Photon-absorbers in 3rd generation light sources operate at power rates of up to 10 kW, or surface densities up to 1 kW/cm^2. This SR power level certainly exceeds that of any possible future large hadron collider. To restrict the surface power density on the photon-stop, its size has to increase with increasing SR heat load. There seems to be no reason (except space limitations in the magnet interconnect) why such a photon-stop could not be shaped like a wedge (or taper) with a longitudinal extension of up to 1 m. The recent VLHC study [1] has shown that the impedance of a 3.5 cm long photon-stop with 1 cm radial and azimuthal extension is small and the impedance decreases with its length. There is no need to extend the stop azimuthaly (which would raise the impedance) because the SR light hits it along a very thin line. The impedance of the photon-stop increases roughly with the third power of the radial extension and it should thus not exceed ~2/3 of the beam-tube radius. Under these precautions, we believe, that a photon-stop will be found in all future hadron colliders. However, there are "hard" limits to the applicability of such a device, which are neither related to the thermal requirements, nor to the impedance. They are of geometrical nature and related to the size of the ring and the magnet length and aperture. Photon-stops are only possible in machines with a large enough aperture and a large enough ring. Figure 5 shows the maximum magnet length compatible with photon-stops placed between the magnets (in a 3 m long interconnect section) as a function of machine arc bending radius, for various magnet apertures in the range 20 – 60 mm. The plot is based on a scheme in which the photon-stop extracts all the SR from the second magnet up-stream (see Figure 4).

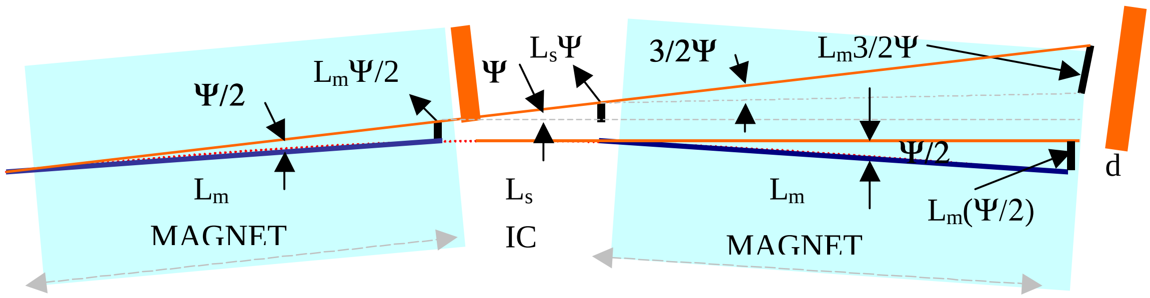


Figure 4: Schematic view of the particle trajectory from the top, explaining equation (5). Ψ is the opening angle of the trajectory segment covered by one magnet $\Psi = L_m/\rho$.

The scheme shown in Figure 4 allows for a maximum distance between the photon-stop tip and the beam. Other schemes, in which the photon-stop extracts a part of the SR from the first magnet up-stream or in which a beam-screen and a photon-stop share the SR load would allow to "soften" this limitation. In the first case, the photon-stop would be brought closer to the beam, increasing its impedance as well as the risk of accidental beam impact. Furthermore it is possible to displace the magnet horizontally with respect to the beam orbit to gain more aperture on the outside of the ring, where the synchrotron radiation is emitted. Such options are interesting for smaller size rings and should be investigated further.

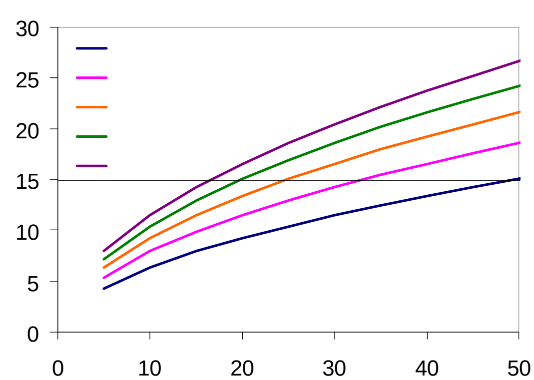


Figure 5: Maximum permissible magnet length to be compatible with photon-stop vs arc radius.

Although not confirmed yet, it is almost certain that some pumping mechanism has to be provided together with the photon-stop, as it is for example commonly done in light sources. In a cryogenic machine it would be most reasonable to use the cryo-pump constituted by the cold bore, which is most efficient in conjunction with a (warmer) liner. Therefore, in the current VLHC, a combined solution of a beam-screen and photon-stop was suggested [1]. In the case, in which the photon-stop is working at full capacity, the beam-screen only fulfills the pump function. In this case the screen could be restricted to the location of the photon-stop only. Whatever the solution, it seems that photon-stops cannot entirely replace the beam-screen and thus the additional aperture requirement for the (local) liner has to be taken into account. Another issue worth mentioning in this context, is the engineering design, which for increased SR power becomes more difficult. For example, the thermal radiation power from the room temperature photon-stop surface is 0.17 W for a 10 cm^2 surface.

Conclusions

Unlike in most of the electron machines, proton machines use high field superconducting magnets operating at low temperatures. Therefore the issue of extracting a synchrotron radiation power heat load becomes more critical and costly. Solutions to the problem of extracting the synchrotron radiation power heat load exist, namely beam screens and photon-stops. Cooled beam-screens such as in the LHC are not only much more expensive in production and operation than a photon-stop solution, but almost certainly become unattractive above a SR load of 30 W/m/beam. Photon-stops are the most economical solution because the heat load is extracted at room temperature. On the other hand there are (geometrical) limitations to the use of photon-stops, related to the magnet size, magnet aperture and bending radius of the particle trajectory. Unless it turns out that shorter magnets are not a large cost burden, the limiting parameter for the use of photon-stops is the circumference of the machine. Given the (current) limitations in magnet technology to <15 T, such an impediment is not of importance in very large energy rings (> 200 TeV cm), which automatically require a large circumference to allow steering of the beams with the limited magnet technology. An increase of aperture, allowing the use of photon-stops as well in rings of smaller size and energy (e.g. below the current proposal for the VLHC in its second stage), is not a recommendable option since it is uneconomical. We are nevertheless confident, that, inspired by the experience with electron colliders and light sources, photon-stops will be an attractive solution to the synchrotron radiation problem in future hadron machines.

Other effects of SR include photo-induced gas-desorption from the PS or beam-tube walls and radiation damping. Increased particle energy and SR (flux and characteristic energy) seem to have only minor effects on the vacuum system and they are mostly of the facilitating kind. For example, larger SR flux and higher characteristic energy reduce the conditioning time. Due to the increase in proton-residual gas cross-section the vacuum quality has to be raised as one goes toward higher proton-energies, but the effect is small. The big benefit from synchrotron radiation is damping, allowing large luminosities at small beam currents.

References
[1] P. Limon et al., “VLHC Feasibility Study 2001”, at www.vlhc.org;
[2] C. Darve et al., “VLHC beam-screen cooling”, Fermilab Technical Division Note TD-01-005, Feb. 2001;
[3] P. Bauer et al., “Synchrotron Radiation Issues in the VLHC-2”, published the PAC 2001, Chicago, June 2001;

Permanent Magnets – *W. Fowler*

The use of permanent magnets in various areas of the proposed accelerator projects has been evaluated and looks promising. Perhaps one of the significant steps that lead to the present emphasis on permanent magnets is the recent data from the Fermilab Recycler where extensive use of hybrid permanent magnets was implemented. By hybrid we mean that iron poles determine the magnetic field and the permanent magnet material acts to excite the magnetic field. Quadrupole, dipole and combined function magnets were fabricated, installed in the Fermilab Main Injector tunnel and commissioned with beam.

G. William Foster gave a talk on the” Construction and Commissioning of the 8 GeV Line and Recycler”. This project consisted of a 0.75km long 8 GeV Line and the 3.3km circumference Recycler named because it is designed to recycle antiprotons at the end of each store rather than dumping them, as is done presently. This project represents the largest use of permanent magnets for accelerator components and when completed qualifies as the 5^{th} largest synchrotron in the world built at a cost of $12 million. Permanent magnets were selected in this case because the energy was fixed at 8 GeV and the field required was below 0.5 T. Other advantages as in this and in other cases of selection of permanent magnets were no power supplies, no cooling water and no energy bill. Strontium ferrite was chosen because it is the lowest cost permanent magnet material per BH (Energy Product) and has high availability since it is now used extensively in automobiles. It has documented good stability over time, temperature and exposure to radiation. The beam line and Recycler magnets were designed with the usual design optimization i.e. to operate the magnetic material at B of approximately 0.5 Br. This extracts the maximum field energy from the permanent magnet material and corresponds to a point on the load line of about 45 degrees. Another important point is to be sure to stay away from the demagnetization “knee” in order to avoid sensitivity to temperature or de-magnetization.

Two characteristic properties of Strontium Ferrite had to be dealt with. The first was that Strontium Ferrite material has a negative temperature coefficient of –0.2% per degree C. Since the Main Injector tunnel temperature varies, the field change in the bending magnets would cause the beam to leave the good field aperture. Incorporating Iron –Nickel alloy with opposite temperature behavior, solves the problem. Approximately 20% of the bending field is lost which incorporating more Ferrite compensates for. The second property of the Strontium Ferrite that has to be accounted for is that the material varies by about 10% in its magnetic properties. The technique that solved this problem was to build the magnet and then measure it. Using this information the amount of Ferrite was adjusted to attain the desired integrated field strength. Since the Recycler is a storage ring the field quality requirement of dB/B is less than 0.01% of total field defect across the 2 inch by 3-inch aperture. The meeting of this requirement was accomplished by EDM machining of end shims determined from the magnetic measurements.

The great advantage of the use of Permanent Magnets, when they can be made to meet the requirements, was demonstrated in the 8Gev Line and Recycler project by the fact that over 500 magnets were produced by a 12-person crew at a rate of 3.5 magnets per day in an area of 12,000 sq. ft. Installation in the tunnel was carried out at a rate of 12 magnets per day.

G.W. Foster also covered designs of permanent magnets for future projects such as VLHC. He described low cost transfer lines using 0.7T permanent magnet dipoles and 30T/m permanent magnet quads.

Ross D. Schlueter as part of the IEEE NPSS Technology Courses gave a short course on Permanent Magnets in which he summarized the theoretical basis for the design of permanent magnets useful for bending and focusing of charged particle beams. He covered the basis of magnetostatics and pure permanent magnet theory in which he presented significant detail. He also showed a recent application in designing a permanent magnet corrector ring capable of providing any desired harmonic mix and which is insert able at any desired location along a beam. Such rings are in present use to null the harmonics of the Q2 system quadrupole for the SLAC B-factory. He reviewed the earlier work on permanent magnets, starting with that by Klaus Halbach and others on the design, testing and use of magnets using rare earth material. He then emphasized the development of the theory for calculating the design of ferrite-based hybrid permanent magnets, which contributed to the design of the Femilab 8GeV Line and Recycler.

Vladimir Kashikhin reported on “Adjustable Quadrupoles for the Next Linear Collider”. This joint effort by Fermilab, SLAC and LBL was initiated about 2 years ago and has resulted in five models for the quads for use in the Main Linacs of the NLC. The NLC design had initially used electro- magnets. Advantages of permanent magnets were stated as 1) elimination of power supplies and water cooling, 2) substantial reduction in cabling, 3) lower operating cost and 4) probably lower magnet cost. Disadvantages were 1) difficulty in meeting one micron stability of quad center during strength adjustment, 2) uncertainty in long term stability and 3) limitation on field strength. The most severe requirement is the stability of the quad center during beam-based alignment. This is a feedback system that requires the adjustment of the individual quad strength by up to 20% in several steps based on beam position monitor signals.

Permanent Magnet Materials

Ferrite	Sm-Co	Nd-Fe-B
Strontium or Barium Ferrite	Sm-Co 1:5,2:17	
Inexpensive	Expensive	Cheaper than Sm-Co
Radiation resistant	Radiation resistance (2:17 good, 1:5worse)	Radiation resistance needs further work
Low Br, 0.38 T	High Br, 1.14 T	Highest Br, 1.43 T
Temp Coef –0.2% per deg C	Temp Coef-0.03% per deg C	Temp Coef –0.1% per deg C

Based on the above table Sm-Co was selected for the initial magnet models. Nd-Fe-B will be investigated as a later step in particular to reduce cost. After looking at a list of possible permanent magnet candidates about 50% looked viable for permanent magnet implementation i.e. about 3321 magnets.

Of the four permanent magnet quad models tested so far the rotational quad gives the best result for the stability of the quad center during strength change. It consists of 4 identical quad sections. Each section is a permanent magnet Sm-Co(1:5) quadrupole. All sections are placed on a V block support and the two central sections can be rotated in counter directions by simple mechanics, providing 20% integrated gradient strength adjustment. Each section is provided with an adjustment in its center by the use of iron shunts. The average field gradient of the assembly is 100 T/m and the aperture is 12.7 mm. The first test run confirmed the design and showed magnetic axis stability in X direction of about 1 micron and about 4.5 microns in the Y direction with good reproducibility. The accuracy of the measurement system for center offset is better than 1 micron.

Brian Watson (Hitachi Magnetics Corp.) covered permanent magnet materials and showed large progress in magnetic properties of rare-earth materials during the past decade. The maximum energy product increases from 200 kJ/m3 to 400 kJ/m3. He showed the technological process of permanent magnet production and noted that large permanent magnet applications decrease the cost of permanent magnets production. Future projects can use new materials with high properties.

Masayuki Kumada presented the Magnet in Magnet (MiM) concept in order to increase the field strength of the 2 Tesla VLHC Superferric superconducting (SSM) magnet. The magnetic field strength of 2 Tesla is limited by a field distortion due to saturation of the iron pole of the magnet. To avoid the saturation, a compact Halbach type 2.1Tesla permanent magnet (PM) dipoles are inserted inside of the both SSM air gaps. The material of the PM where the external filed opposes to the magnetization direction of the PM material can be chosen so that it does not demagnetize. The field strength of the SSM 2.0 Tesla as a bipolar mode. The resultant field changes from 0.1 Tesla to 4.1 Tesla. The diameter of the PM inserts is roughly 100 mm and the necessary SSM excitation current is about 250 kA. The field stability of the MiM magnet can be performed by feedbacking to the power supply. The cost of the PM is modest and comparable to the SSM.

Jim Volk proposed to start at FNAL investigation of radiation damage of permanent magnets. Two magnets with a known load line one with high coercivity material and another with lower coercivity material should be built and irradiated until a noticeable change in the field is observed. The lower coercivity magnet should show loss in field with less radiation than the higher coercivity magnet. The magnets should then be disassembled and the magnetic material re magnetized. The field after re-magnetization should be the same as the original field. Similar magnets should also be built and not irradiated to measure the effects of aging in the magnetic system. The manufacture of the magnetic material should be carefully controlled at all steps to ensure uniform and small grain size.

Magnets for Hadron Collider Interaction Regions – M. Lamm

Introduction

Particle beams are brought into collision through the use of interaction region magnets. For the many reasons listed below, these magnetic elements are some of the most challenging in an accelerator design and thus demand special attention.

General Requirements for IR magnets

The focusing requirements and the subsequent interaction by-products make the operational requirements more stringent than the arc magnet counterparts. The following issues have been identified as important to interaction region magnet design:

High gradient/field and large aperture

- As these magnets form the final focus, they are located as close as practically possible to the interaction regions. This requires high gradients to achieve the required β^* with a limited focussing lever arm. The large aperture is required to accommodate absorbers in the beam pipe to intercept the large radiation/heat deposition due to interaction debris. It is also needed to account for lattice requirements for large dynamic aperture and for beam separation from a beam-crossing angle. For a 200 ìrad crossing angle the beam is separated by 4 mm at the front face of the first LHC IR quadrupole.

Excellent field quality

- This is driven by the crossing angle and luminosity requirements for the IP. A figure of merit for field harmonics at the upper end of injection and beta squeeze is one unit of unallowed harmonics. Harmonics of this order can be compensated by a scheme of local correctors.

High radiation environment/heat deposition

- The proximity of the magnets to the IP puts a significant radiation load on the magnet. For the LHC, ~900 Watts/side of debris is generated at nominal luminosity and energy. Of this, 200 Watts is deposited in the cryogenic system through the beam tube and beam tube liner. Aside from the cryogenic load, some of this debris will interact directly with the magnet, which can cause the magnet temperature to be raised and cause a quench. The radiation can degrade the magnet components (7 years of LHC operation translates into 20 MGy, which causes the epoxy in G-11CR to disintegrate) and can cause activation of magnet and shielding.

Alignment and mechanical stability

- Magnet alignment contributes in three major ways to the proper operation of the accelerator. First, misalignment leads to luminosity loss, by steering the beams to the wrong location in the IP. Second, misalignment causes the beam to populate off- axis areas of the aperture and thus become susceptible to harmonic errors that grow in powers of the radius. This leads to a decrease in dynamic aperture if not properly accounted for with local correction. Finally, transverse misalignment can lead to a reduction in physical aperture, as beam pipe apertures are already reduced by absorber materials to ameliorate the problems listed in item 3. Typical transverse alignment goals are 300-500 microns, 1-2 mm longitudinally, 1 mR in roll and 100 microradians in pitch and yaw.

Powering and quench protection

- The protection goals for IR magnets are comparable to other superconducting magnets: namely limiting the peak voltage to ground to 1000 V and limiting the peak temperatures to 400 K. These goals are challenging because of the high field/large aperture, which translates into high currents and/or large inductances and large stored energies. Inner triplet magnets are typically powered in series, with the possibility of varying the field in one of the triplet quadrupoles for accelerator studies.

Examples of IR Magnets

Several types of IR magnets are in prototyping or R&D phases, while others are under consideration for future machines. These include:

- LHC IR quads: Fermilab has completed a model magnet program, has tested the first full-length prototype, and is gearing up for a 20-unit production run
- LHC IR quad upgrades (Nb_3Sn): under active consideration
- LHC IR HTS quads…embedded into detector
- VLHC-1 IR quads (Nb_3Sn): see the VLHC Design Report for detailed description
- VLHC-2 IR quads (BNL Nb_3Sn or HTS)
- Permanent magnets for IR Quads

IR magnet development program

The IR quadrupoles for the Tevatron, RHIC, and LHC are made from Rutherford style NbTi cables. The 70 mm aperture LHC inner triplet quadrupoles operate in superfluid with a peak operating gradient of 215 T/m. Future accelerator applications will require a combination of higher gradient, possibly larger aperture and higher heat loads. This means building magnets with Nb_3Sn or High Tc materials.

The upgrade for the LHC IRs is an excellent opportunity to use Nb_3Sn technology for a production series of accelerator magnets. The experience from all phases of the magnet production, from cable procurement through construction and test will be invaluable for the VLHC program.

Any future IR magnet program including those mentioned above will required a detailed understanding of the operational conditions, the field strength requirements and the radiation heat load. The key issues for radiation are:

- radiation heat depositions (transverse and longitudinal distributions)
- radiation load on different elements of magnet design
- IR component activation

Magnetic Measurements – *H. Glass*

Introduction

Magnetic measurements are an essential part of the R&D program for magnets for new facilities. Some magnets will only need an extension of present techniques; others will require a certain amount of development of new measurement tools.

Measurement activities at Magnet R&D centers

Activities at Fermilab from which we should continue progress toward measurement requirements for future magnets include:

–*LHC IR quadrupoles*: we have built a new test stand for horizontal tests of the LHC Q2a/Q2b IR triplet quadrupoles. The test stand has the capability to provide superfluid He to the magnets. The stand is long enough to accommodate 2 quads in a single cryostat; this implies we are gaining valuable experience in testing magnets or magnet strings up to ~16 m in length.

–*Nb3Sn model magnets*: the measurements of these magnets is being done at the Vertical Magnet Test Facility, which has been operational for the last few years. This allows us to test short models, typically 1-2 m cold masses, in an LHe dewar. Two magnet designs have active test programs; these are the cos θ and racetrack (common coil) designs.

–*VLHC Stage-1 prototype*: Tests of the SC transmission line have been done and the concept has been validated. Some prototyping of measurement devices is ongoing, including a multi-element Hall array for transverse field shape measurements, and a rotating coil as described below.

–*NLC permanent magnets*: We have made models of three different designs of permanent quadrupoles. Each model tries a different technique for maintaining the magnetic center to 1 μm. One of the models, made of counter-rotating cylinders, shows very encouraging results.

Activities at other labs are also very strong. SLAC has made good progress on making small diameter rotating coils for strength and alignment studies of permanent and electromagnet designs for main linac NLC quads (Z. Wolf et al.). The CERN measurement group has been very active in main arc dipole and quad measurements for LHC; they have been developing probes using ceramic materials which can be used in cold bore measurements (L. Bottura et al.). LBL has demonstrated a 16 T dipole (S. Gourlay et al.). It is anticipated that nearly all the labs will report on ongoing and future measurement programs at the International Magnet Measurements Workshop to be held later this year.

Texas A&M is vigorously pursuing very high-field magnets R&D. They measure field quality in two ways:

1. Use of tangential coil with bucking using step rotation integration
2. Use of a Morgan coil rotating at fixed rate; each coil is read out with a phase-lock amplifier.

Arc dipoles for VLHC Stage-1

R&D for measurements of VLHC Stage-1 arc dipoles will of course have to make rapid and significant progress in the next few years, because of the parameters associated with these magnets. The parameters affecting measurements include:

- Magnet length of 65 m
- Aperture (on center) of 20 mm
- Gradient profile (~5-9%/cm)

A first sketch on how to measure these magnets was developed for the VLHC Design Study. This uses a rotating coil which is inserted into the open part of the C magnet from the side, as shown in Figure 1. The two probes, one for each aperture, are attached to a strong back which is mounted to the top of the magnet laminations and provides precision positioning. The probes could be made nominally with a length of 6.5 m, which means that by sliding the probe along 10 longitudinal positions, the entire magnet length could be measured.

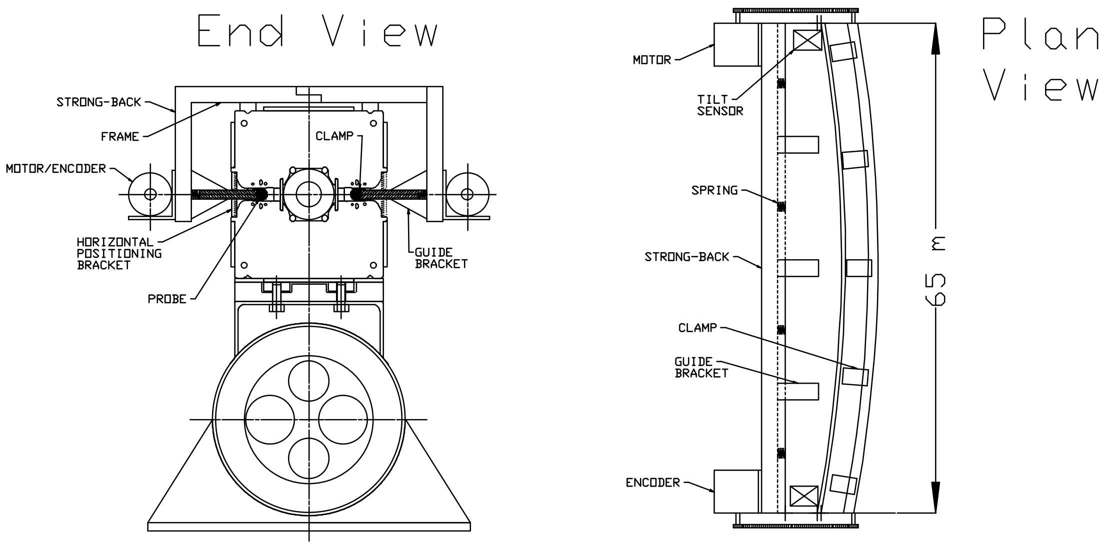


Figure 1. Proposed rotating coil mechanical layout for arc dipole measurements.

VLHC Stage-2 magnets

For the VLHC Stage-2 magnets, we can expect to use the techniques developed for the LHC and older types of magnets. That is, a combination of rotating coils to measure the harmonic content with stretched wire systems to measure integral strength and alignment will probably work. The present high-field magnet program, based on the use of Nb_3Sn superconductor, requires simpler (less expensive) cryogenics than the superfluid LHC IR quads, only needing a 4.5 K operating temperature. The 40 mm aperture may present some challenges for a rotating coil system, since lower coil radius will result in reduced signal size. The effective aperture size for a probe may be further reduced by the presence of a beam screen. This may be mitigated by the very large signal one will expect for a 10 T field. Warm measurements, however, will have greatly reduced signal size, but we have already gained experience in measurement of small signals, e.g., we routinely make corrector strength measurements in warm Tevatron spools.

Permanent magnets

Fermilab has been very active in permanent magnet technology since the Recycler development, which used thermally-compensated Sr-ferrite ceramic magnets. More recent activities include using high-field SmCo (and also NdFeB) permanent magnets to do R&D for NLC main linac quads. Measurements have focused on the severe alignment requirements of these magnets (~1 μm). We have used the single stretched wire technique with promising success: with our current stages, we have been able to obtain precision measurements on the order of a few microns. Further investment in high accuracy stages will be necessary to achieve the measurement goals.

TESLA main linac quadrupoles

These magnets are superconducting, cos 2θ design operating at 2 K with horizontal and vertical dipole correctors built into a single package[1]. They have 60 T/m gradient, and only a 100 A operating current. Other parameters of consequence to magnetic measurements include: aperture diameter = 79 mm, and total magnet length = 86 cm. Field quality requirements at 30 mm radius are 3×10^{-4} for skew quad, and 10^{-3} for higher orders. Alignment tolerance is 0.1 mrad. Measurements of field axis and orientation will probably be done using stretched wire. While US groups have not been actively involved in these measurements, one area of US participation in TESLA could include R&D in stretched wire technology and measurement support for the large number of magnets required.

R&D plan and costs

The first key point is that future progress depends on more staffing. At Fermilab, for example, we now have ~3.5 FTE physicists devoted to magnetic measurements. We will need to increase this to 4-5 FTE in order to aggressively pursue R&D on all the measurement activities listed above. Other labs are in a similar situation.

It will also be necessary to increase materials budgets to purchase high-accuracy stretched wire stages; buy materials for probe forms, motion control systems, and electronic readout for rotating coil systems; and to do development of the VLHC Stage-1 magnet measurement system. A detailed cost proposal should be developed soon, but one may expect materials and supplies costs for each measurement laboratory (Fermilab, SLAC, BNL, Texas A&M, etc.) to be in the $150k to $300k range per year over the next 5-6 years.

Quench Protection – *A. McInturff*

Assumptions: This note will concern high J_c, J_{cu}, 2 kA/mm^2 windings producing fields of 12T or greater to be used as accelerator optics magnets. The following will be based on a multi-10kA/turn devise which should be approximately length independent utilizing an active heater intervention technique (Tevatron style). These heaters are a laminate of stainless steel, copper, and Kapton foil/glue combination with the appropriately determined geometry. This technique is in a similar circumstance being used to protect the present machine magnets and those in the near term. The application to the High Field A-15 (Nb_3Sn) super conducting magnet windings requires advancement in its application.

1st step is to design a reasonable winding. A starting place would be at the 95% of the critical current of the cable on the load line of the winding at the operating current with a desired aperture of 3 to 4 cm.

$$\mathbf{J_C(Nb_3Sn\ Goal) \Rightarrow 3kA/mm^2\ at\ 12T,\ 4.3K}$$

[1] TESLA Design Report, Chap. 3, [redacted]

And at quench J_{Cu} = 2kA/mm^2

Design parameters => 20kA/turn *L* = 1mH/m, and stored energy ~0.12megajoules/m

RRR– an open design parameter but ~ 7– 15

An appropriate *L*/R ~ 50ms

Although a detailed MIITS calculation is needed to be performed on the final conductor configuration with a peak design temperature in the ~200K range, I will presently take a few estimates from previous work to illustrate.

At the first cut the protection heater would have to switch a coil volume equivalent to

L/R = 50ms or R/m = 1x 10^{-3}/5x10^{-2} = 0.02 ohms/m

If the 7K RRR ~ 15 then the average RRR ~ 5 is appropriate

R(300K)/m = 3.3 x 10^{-3} ohms/m-turn

Derived from the TAMU version of Tevatron Tripler

A(cu) = 10mm^2

If at a field of 15T J_c **(non- cu area) =24kA/mm^2 results** in a turn cross section **A(turn) = 18.4mm^2/turn**

At 20kA/turn a 20ms detection time => 8 MIITS

If the RC time constant of the protection heater circuit is adjusted to 16 – 20ms for an adiabatic heater temperature of 150K, then 7K is reached in the conductor in <10ms. Therefore the hot spot has **12 MIITs maximum** when the conductor under the protection heater switches. After 20ms into the induced quench cycle the down ramp will be **>400kA/s where the quench-back rate is on the order of 10kA/s.** The MIITs budget for this conductor is on the order of **40 MIITs; therefore** we can consider the following scenarios.

If *L*/R = 50ms ~10MIITS => total ~18– 20MIITs <200K

Or if only 50% coverage or RRR~30

If *L*/R = 100ms ~20MIITs => total ~28– 30MIITs <250K

Because this is a distributed heater the voltages will not add but cancel with the inductive ones to first order. This should result in a few (<2) hundred volts with respect to ground/meter. The hot spot should be **<**12MIITS out of <30MIITS therefore the temperature difference between it and the coolest part of the windings should be <76 – 50K (typical measured <50K)

The protection heater will have to be more efficient than those in present use for the model magnets are. They will be fabricated from 13-micron thick stainless heater material powered to a 40 to 50 w/cm^2 level up to 150K adiabatic temperature with an insulation barrier of Kapton and glue of 25 microns. This will therefore require about a quarter of the power.

But even this rather crude example shows that one can actively protect a winding at 2kA/mm^2 with 50% heater coverage comfortably. Or have a single unit failure and still protect the coil.

Very High Field Superconducting Magnets – *S. Caspi*

Progress in high field accelerator magnets began when Nb_3Sn superconductor was first introduced as a possible conductor replacing NbTi. Starting 20 years ago with a 5 Tesla field, Nb3Sn dipoles are now approaching a central field of 15 T (Fig. 1)

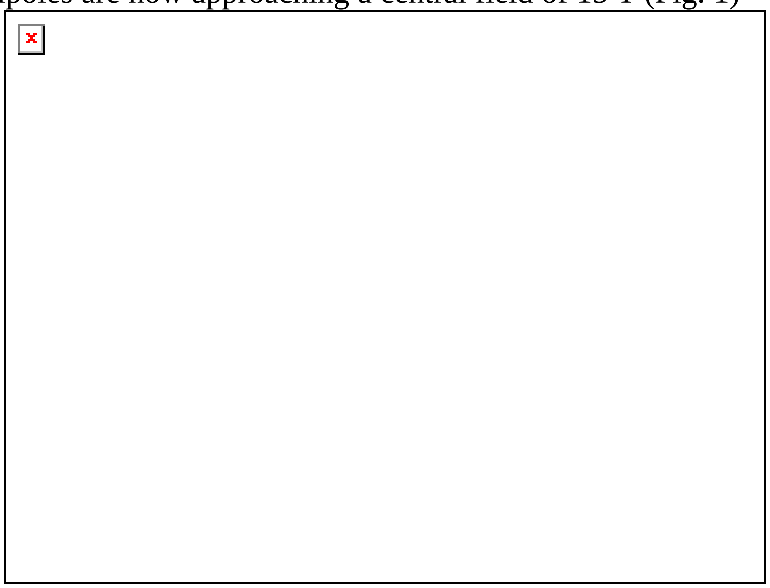


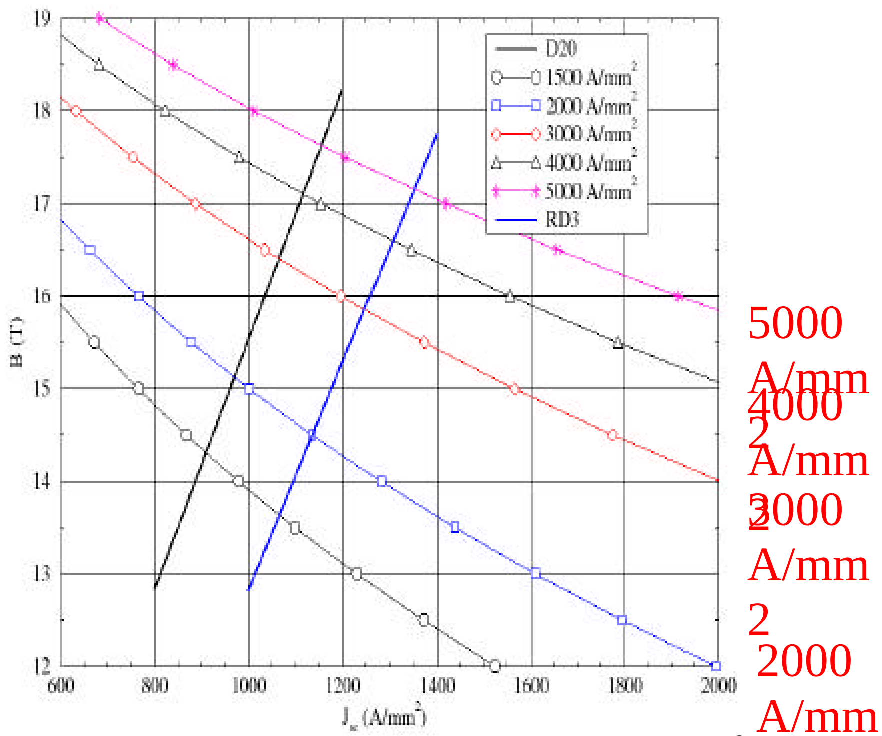
Figure 1 Progress in Nb_3Sn dipole magnets in the past 20 years.

As we expect an increase in J_c to 3000A/mm^2 @12 T, dipole fields could be raised from their current values of 14.7 T to over 16 T. A potential additional increase in current density to 5000 A/mm^2 will raise the field by an additional increment of 1.3 T (Fig. 2). It is possible to assume that Nb_3Sn dipole magnets could potentially reach a maximum operating field of 17.5 T at 4.2 K and 18 T at 1.8K. From that point of view and considering the distant future of the VLHC, high field dipoles with an operating field of 15 Tesla should be considered as viable candidates for the next hadron collider.

Current Density

On going R&D on raising the current density of Nb_3Sn from the present level of 2000-2200 A/mm^2 to 3000 will increment the field of high field dipoles by 1.3 T and will make magnets with fields of 16 T possible. Any additional increment of 1000 A/mm^2 beyond the 3000 A/mm^2 level will raise the dipole field by 0.6-0.7 T

The current density in the copper is much less of an issue compared with lower field magnets. For example, magnets with a target-operating field of 12 T using present conductor will have to account for J_{Cu} of 2000 A/mm^2. Raising the current density at 12 T to 5000 A/mm^2 will similarly raise J_{Cu} to 5000 A/mm^2. However if we raise the operating field as improvements are made to J_c, the current density in the copper will be lowered. For example J_{Cu} at 18 T with J_c as high as 5000 A/mm^2 will not exceed 1400 A/mm^2. This is good news both from a protection point of view and a cost point, as it will allow us to reduce the amount of copper in each strand from the current ~50% level to 20%. Incorporating low copper ratios in strand production will therefore raise J_{Cu} to values that are only as high as 2500 A/mm^2 and the use of any additional external copper may not be needed.



We point out that in the RD3 dipole J_{Cu} reached 1150 A/mm^2 at its short sample of 14.7 T. It was also observed that upon a quench the magnet temperature did not rise above 200 K

Figure 2 Central-field as a function of current density in the superconductor shown here for D20 (tested to 13.5 T) and RD3 (tested to 14.7 T). Short sample current densities above 3000 A/mm^2 are hypothetical.

Training

So far there is experimental evidence that Nb_3Sn magnets can undergo training but may also be voided of training. The Twente dipole (11.3T) and RT1 (12T) have shown little or no training. Magnets D20 (13.5T) and RD3 (14.7T) have undergone several 10's of quenches before reaching their short sample limit. It was also observed in RD3 that the origin of training quenches did not come from locations around the "poles" but from areas well within conductor blocks. Based on such measurements and quench velocities we may conclude that training in high field magnets is not necessarily localized but is rather associated with motions of large conductor blocks.

The cost of training in high field magnets can be high. The cost increase as the field increases will double again as we do R&D on double bore magnet (such as the common coil). The stored energy per m length in RD3 is 1.2 MJ/m compared with 0.5 MJ/m in the LHC (both channels).

We should also be aware that at high fields the cost of "safety margins" is getting high. R&D on increasing the current density from 2000 A/mm^2 to 3000 A/mm^2 will cost 10's of M$. That 33% increase in current density will buy us 1.3 T or a 10% margin a price we will be happy to pay if no training can be assured.

The pay back in reduced training in high field dipole is therefore worth 100's of M$. Finding new investigative ways on the origin of training and ways to avoid it should therefore take top priority as we try to push towards higher fields.

Lorentz Forces and Structure

Raising the fields from 10 T to 15 T has doubled the Lorentz force. That value was doubled again as double bores were introduced in geometry's such as the common coil.

Magnet	Field (T)	Fx (MN/m)	Fy mid-plane(MN/m)	Fz (kN)	Bore (mm)
LHC	8.3	3.4	-0.74	250x2	2x56
RD3	14.0	7.7x2	-2.2	261x2	2x25

Construction and assembly procedures of very high field magnets are undergoing substantial changes compared with technologies inherited from NbTi magnets. The use of bladders and simplifications such as the use of “no-skins” to pre-stress coils will contribute to an additional cost reduction of such magnets. The increase in the Lorentz forces can be accommodated with new structures, some of which could be made even less expensive than those used with NbTi at lower fields.

Bladders reduce the need of high tolerance in coils and components, they conform to irregular surfaces, apply uniform loading, excellent way to measure room temperature pre-load, ease of assembly and disassembly and allow for reusable coils or structural designs

Conclusion

Once we use Nb_3Sn technology in our magnets, the increase in cost from 10 T magnets (where NbTi can still be used) to 15 T magnets is well offset by a decrease in the size of the accelerator.

Superconducting Magnets for a Muon Collider or Neutrino Factory – *M. Green*

A muon collider or a neutrino factory requires the extensive use of superconducting magnets. The two types of muon machines are similar in their design. The primary difference lies in the muon cooling system and the acceleration system for the two types of machine. It is said that the neutrino factory can be the front end of a muon collider. The primary difference between the front end of a muon collider and the front end of the neutrino factory is the extent to which the muons are cooled before acceleration. The front end of both types of machines is a string of superconducting solenoids that both direct and focus the muon beam[1].

The front end of both a muon collider and a neutrino factory starts with a 20 T capture solenoid around a target that is impinged by a high intensity (1 to 4 MW) proton beam. This magnet is a hybrid magnet that operates in an extremely high radiation environment. The capture solenoid is DC, so the outsert portion of the magnet is a superconducting solenoid that develops an induction that is as high as 14 T in its own right. The field in the capture system decreases adiabatically as one moves down the channel away from the target. As one moves downstream from the target all of the solenoids are superconducting. Room temperature shielding keep the superconducting magnets from turning normal under the high radiation load from the target. It is proposed that at least some of these solenoids be made using a cable-in conduit conductor.

Once the pions produced at the target are captured, they must go through phase-rotation. The phase-rotation process slows down the high-energy particles and speeds up the low-energy particles. Phase-rotation can be accomplished using low frequency RF cavities or using an induction accelerator. In both cases the particles are directed using a solenoidal field. High current density superconducting solenoids that produce an on axis induction of 1.25 T to 3 T are needed inside the RF cavities or the induction accelerator. These solenoids can be challenging from a cryogenic standpoint because there is very little room for the cryostat and the magnet cryogenic services.

Once the muons have been phase-rotated, they must be cooled to a low emittance so that they can be accelerated to high energy. The degree to which the muons must be cooled depends on the size needed for the final beam. A muon collider requires much more muon cooling than does a neutrino factory. Ionization cooling has been proposed to be used to cool the muons. Ionization cooling has alternating acceleration and absorption method. The absorption removes both longitudinal and transverse momentum. The acceleration phase puts back the longitudinal momentum lost in the absorber. Hopefully, multiple scattering during the absorption phase does not heat the beam more than a cell can cool the beam. Several cooling schemes have been studied. All of the schemes require RF cavities that are in a magnetic field. The absorber, which is smaller than the RF cavity, is also in a magnetic field. A number of the cooling approaches will require that the field be flipped within either the RF cavity or the absorber. The solenoids in the cooling section will be challenging because there are large forces on the coil. Later stages of muon cooling will require large on axis fields. The highest on axis fields that have been discussed approach 30 T. A point in the cooling channel where the highest field occurs is where the magnet aperture is the smallest. The cooling channel solenoids begin to resemble accelerator dipoles in that the highest current density conductor is needed in the highest field region of the cooling channel. The continued development of A-15 and HTS conductors will benefit the muon collider. The cooling channel for a neutrino factory does not push the superconductor as much.

The first stages of muon acceleration will use solenoidal focusing as part of a superconducting linac. As one moves up in beam energy solenoidal focusing is replaced by quadrupole focusing. The size of the focusing magnets and bending magnets in the acceleration section is dictated by the size of the muon beam leaving the muon cooling system. The final stages of muon acceleration will either occur in a re-circulating linac or an FFAG. The peak field for any of these magnets is about 7 T. The acceleration section will see some heating from muon decay (about 1 W per meter of length). The decay product heating can be reduced through the use of a room temperature water-cooled liner.

The storage ring for either the muon collider or the neutrino factory requires relatively high field accelerator type magnets to bend and focus the beam. In both cases it is desirable to reduce the length of the bending sections of the storage ring. From a practical standpoint bending magnets that produce a central induction of 6 to 10 T would be attractive. High gradient quadrupoles are probably not needed for the neutrino factory storage ring, but they are needed in the collider storage ring in the region around the collision point. The dominant factor in either the muon collider or the neutrino factory storage ring is the heating due to muon decay. Depending on the type of machine and its design, this muon decay heating will be from 0.1 kW to 3 kW per meter of magnet length in the storage ring. The portion of this heating entering the cryogenic region of the magnets must be less that 1 or 2 W per meter. This has lead to some unusual magnet designs or large aperture magnets that have a room temperature beam absorber within the magnet bore. Some of the magnet designs proposed for the muon storage ring require the use of niobium tin or some other high field conductor. The development of the muon storage ring will benefit from continued development of high current density conductors that operate at fields above 12 T.

Since the magnets in the muon collider or neutrino factory use high current density conductor, the key magnets in the system should be built and be tested. Training is a potential issue even for superconducting solenoid magnets. The magnets in the phase rotation system and the cooling system should be modeled. The magnets for the re-circulating linacs and the storage ring will be a challenge; so model magnets should be built. If the muon collider or the neutrino factory is going to be a part of the future of high energy physics in the United States, the superconducting magnet modeling work should be done along with conductor development. Conductor development for the high field magnet work in the United States will benefit the muon collider and neutrino factory as well as the VLHC.

[1] M. A. Green, E. L. Black, R. C. Gupta, M. A. Iarocci, et al, “The Role of Superconductivity and Cryogenics in the Neutrino Factory,” submitted to CEC-ICMC-01, Madison WI, 16-20 July 2001, to be published in Advances in Cryogenic Engineering **47**, LBNL-48444, July 2001

Superferric Magnets **-** *G.W. Foster*

The superferric magnets are the very attractive approach for the future staged colliders. One of the proposed options for future VLHC is to build as large as possible in perimeter tunnel, install there superferric magnets of Stage I and upgrade later the accelerator with help to Nb3Sn high field magnets to the maximum possible energy. VLHC Design Study Report based on this scenario was presented by P.J.Limon at the Snowmass plenary meeting.

V.S.Kashikhin gave a talk on the “VLHC Stage I 2 Tesla Superferric Magnets” which under design and model tests in Fermilab. The 2 Tesla fields with good quality are achievable using holes in poles to correct saturation effects. Several short models were tested. The test stand with two 6m-length magnets, Hall probes station, 100kA power supply and current leads are under construction now. He also presented promising concept of 3 Tesla transmission line magnet with cold iron core.

Single turn winding and small pole correction coils give the possibility to correct iron saturation effects. The field with negative gradient goes from the “nature” of C-shape magnet. The field with positive gradient obtained by magnet rotation. Focusing and defocusing magnets have the same cross-section and both main and correction windings. It was also proposed to install inside each half-cell permanent magnet rotational multipoles as correction elements.

G.W.Foster observed various options of superferric magnets: 2T transmission line magnet, SSC 3T superferric magnet, RHIC 4.5T cold iron core magnet.

P.McIntyre presented the Texas A&M 3T magnet program for SSC. There were built and tested four 34m length magnets with good results. He also showed that it is possible to increase for such design (window frame magnet with cold iron) the field level up to 6 Tesla. The saturation effects for these magnets eliminated by separate excitation of winding coils from 3 different power supplies.

B.Palmer presented the cost analysis for future VLHC. He showed that possible minimal cost of magnet system for the Stage I is in the range of 4-5 Tesla. Proposed solution is shell type two bore magnets. Combined function magnets obtained by winding turns arranged in such a way to add skew quadrupole field to the main dipole component.

M.Kumada presented the Magnet in Magnet (MiM) concept where two permanent magnet dipoles incorporated into both air gaps of 2 Tesla transmission line magnet in order to increase the field strength up to 4.1 Tesla. Bipolar power supply is used to change the field from 0.1 T to 4.1T.

All presented concepts were discussed. Only careful comparison of all designs with cost optimization and analysis of whole accelerator needed to choose the best magnet for the VLHC.

R&D Issues and Planning

Conductor

The primary need for conductor R&D is in conjunction with the intermediate and high field magnet options. The low field design options utilize NbTi superconductor, which has been optimized as a result of the previous R&D programs associated with the SSC and LHC. Approximately 25 M$ over a period of 8 years was invested by DOE HEP in the development of high current density, small filament size NbTi for the SSC. Also, NbTi is being produced on a large scale for commercial MRI markets, and thus NbTi production has achieved the economies of scale.

Magnet designs in the 10-15 T range require a high field conductor, and Nb_3Sn is the high field conductor that presently offers the best combination of performance, availability, and cost. However, Nb_3Sn conductor design has not been optimized for HEP applications, and the modest commercial demand has not provided the incentive for industry to scale up production. In recognition of this situation, DOE HEP has initiated a modest conductor development program aimed at producing a cost-effective Nb_3Sn conductor. A Conductor Advisory Group, consisting of magnet designers (BNL, FNAL, LBNL, and TAMU) together with materials scientists (U. Wisc, Ohio State U. and

LBNL) developed a multi-year plan and program goals focused on HEP magnet needs. This program his been underway for about one year, and has achieved considerable technical success. One of the key parameters, critical current density, has been increased from the 2000 A/mm^2 level to a world record 2600A/mm^2. R&D is continuing to meet the other technical goals, such as reducing the effective filament size in order to reduce field distortion at injection. Highest priority has been given to industrial development, with testing work being performed by the National Lab and University Groups on their base programs. However, lack of adequate testing facilities for these new, high current density conductors is hampering further development.

The long-range plan for this program calls for a production scale-up phase to follow this first phase, which is devoted primarily to improved technical performance. However, the conductor scale-up effort will require a significant increase in funding. Scale-up requires processing multiple units (billets) in order to demonstrate process uniformity and to justify the use of production-scale equipment. It is important as well to insure that there is competition, so at least two companies should be encouraged to participate in this program. This scale-up effort will require a time and funding commitment of the same order as the SSC NbTi effort.

Magnets

Due to recent advances, magnets with fields in the range of 2 – 15 Tesla can be considered for a variety of applications. However, the time and resources required to develop the technologies vary significantly. For example, low-field superferric magnets such as the FNAL Transmission-line magnet or the Texas Accelerator Center (TAC) magnet could be brought into production in less time than it would take to dig a tunnel for a new machine. High field magnets based on Nb_3Sn would require longer development time, on the order of a decade, depending on funding levels.

In terms of the next large-scale application of magnet technology, there is an implicit goal to reduce the cost per Tesla-meter by at least a factor of two relative to the SSC dipoles. Conventional approaches have reached an asymptote, and meeting expectations on cost reduction demand consideration of alternate magnet designs and technologies. Smaller-scale applications, such as IR quads for both linear and hadron colliders, have operational requirements that demand very high performance levels. During the workshop many design options and issues related to cost and performance were identified and have been described in this report. Some examples are:

- Magnet length

By reducing the number of magnets and hence the number of expensive interfaces, increasing the magnet length has clear cost saving advantages. The issues involved (which can only be studied by building magnets) are: mechanical stability and alignment, transport and magnetic measurements. The possibility of photon stops will also be a factor in the cost vs length issue.

- Coldmass design

Several magnet geometries have been presented, but a lot of work, integrated with input from accelerator physicists, is required to evaluate all the options and choose the right combination of cost and performance.

- Aperture

With higher energy machines there is a trend towards smaller apertures. Cost savings come from a reduction in the amount of conductor required for a given field and support structure. Eliminating beam screens which take up precious aperture and dealing with beam instabilities are the challenges.

- Support systems (cryo, quench protection, etc.)

Designing magnets that do not require complex support systems has obvious cost saving potential. Helium inventory, heat loads, warm- vs cold-iron designs, quench protection requirements (active vs passive), and copper current density are all topics for intensive study.

- Large scale production and testing

Large scale, industrial production is an absolute necessity when considering fabrication of thousands of magnets. Significant R&D effort is necessary to provide manufacturable designs. Past experience has demonstrated a lack of sufficient consideration of the value of robust mechanical designs at the end of the R&D program. Both SSC and LHC magnet designs were not adequately prepared for industrial fabrication until very late in the procurement process, leading to higher than necessary contingencies.

- Field quality

Cable size control during heat treat process for Nb_3Sn, cross-section designs that reduce persistent current effects and extending dynamic range (iron saturation control) are a few of the issues needing study.

- High gradient IR quads (conductor development (HTS) and rad hardness)

High gradient quadrupoles represent the greatest challenge in terms of performance. High fields and very large heat loads require either innovative use of Nb_3Sn or HTS, which still needs to be proven to be a viable material.

- Magnetic measurements

Long magnets with smaller bores require development of new techniques for magnetic measurement.

- Superferric magnets

Further development of superferric magnets includes fabricating prototypes of 2 Tesla Transmission-line magnets, explore a 3 Tesla cold-iron option based on the Texas Accelerator Center magnet design and MgB_2 conductor performance for possible transmission lines at 20 K.

- Permanent magnets

Permanent magnets have now become a viable alternative for a wide variety of applications. A large number of topics need more development: thermal and radiation stability, active and passive correction systems, adjustability, hybrids and cost optimization.

The U.S. programs, complementary in approach, manage to pursue a significant subset of the major R&D issues. But, given the relative importance of magnet sub-systems, either as significant cost drivers and/or providing a critical function, the current level of R&D effort is disproportionately low. For example, development work on medium-field magnets as a VLHC option, is non-existent. In the case of other options, most notably high field magnets, progress towards achieving a technological base from which to launch a development program has been hampered due to lack of adequate support. Realistic evaluation of the broad range of magnet technologies, ranging from permanent magnets to high field, superconducting dipoles, requires a more aggressive program. The formula for success requires a substantial increase in the base magnet program along with an increase in collaboration (sharing lessons learned and facilities) between magnet programs in the U.S. and abroad. A 10 – 15% per year increase for the next 3 – 4 years seems modest considering the scope, but would have a significant impact on productivity and status. An integrated approach, combining input from accelerator physicists and evaluated using a standard cost model is necessary to arrive at a cost/performance optimized design. It was suggested that the RHIC model be generalized and used as a basis for design comparisons. The very successful VLHC Design Study is an excellent example of the combined approach (and effort) needed to evaluate accelerator/magnet options and should be expanded to include other possibilities and parameters. More details on magnet R&D issues and plans can be found in ***T2_MagR&D_0814.pdf***.

Summary

The US magnet R&D programs have not totally recovered from the demise of the SSC. The resources required to bring the existing magnet technology options to a point where they can be reliably costed and considered for use in a collider design, does not currently exist. In addition to increased R&D funding, there is need for a global cost framework to compare and evaluate design options. Since the RHIC dipoles are the only US example of industrial procurement, it is suggested that those costs can be used as a basis to develop a comparative cost model. The magnet programs need to work closely with accelerator physicists to push all parameters to the limit and arrive at the most cost-effective combination of magnet design and machine performance. There has been informal activity in this direction, for example, at the VLHC Workshops, but there is a need to formalize this activity in a more coherent way.

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[i] V.V. Kashikhin and A.V. Zlobin, "Magnetic Designs of 2-in-1 Nb_3Sn Dipole Magnets for VLHC," IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 2176.

[ii] D.R. Chichili et al., "Mechanical Design and Analysis of Fermilab 2-in-1 Shell-Type Nb_3Sn Dipole Models," IEEE Transactions on Applied Superconductivity, v. 11, No. 1, March 2001, p. 2288.

[iii] V. Kashikhin and A.V. Zlobin, "Conceptual Designs of 2-in-1 Nb_3Sn Arc Quadrupole Magnets for VLHC," Fermilab, TD-01-019, March 2001